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Physiological Burden of the S10 Respirator

S. Scanlan and W. Roberts

DSTO-TN-0380

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Combatant Protection and Nutrition Branch
Aeronautical and Maritime Research Laboratory

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ABSTRACT

It is well accepted that wearing a respirator increases the physiological load imposed on the user. However, there is little quantitative evidence of the impact of respiratory protection on thermal strain imposed on the user as a function of the total individual protective ensemble (IPE). This pilot study aims to use the novel technique of Thermal Imaging (TI) to assess the heat status of the face and thermal strain associated with wearing the S10 respirator. The physiological (rectal and tympanic temperatures, heart rate), psychophysical (thermal sensation and discomfort, perceived exertion) and thermal effects (thermal imaging) of the S10 respirator were measured in four healthy males (31±4.5yrs). Each subject completed two 45 min trials consisting of acclimation (10 min), treadmill walking (30 min) and rest (5 min) in a hot environment (30°C dry bulb and 60% relative humidity), while wearing the UK MK IV overgarment with the S10 respirator (MASK) and without (CON). Generally, there was no additional thermal strain while wearing the S10 respirator. However, subjects reported thermal discomfort of the face as being significantly ($p<0.05$) more uncomfortable after 30 mins of exercise compared to being unmasked. In conclusion, the mask partially inhibited evaporative cooling of the face giving the user the perception of being more heat stressed than when unmasked, which was not matched by the recorded physiological strain. It is recommended that the design of the respirator require no significant alteration to reduce any perceived thermal load.

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Published by

DSTO Aeronautical and Maritime Research Laboratory
506 Lorimer St
Fishermans Bend, Victoria 3207 Australia

Telephone: (03) 9626 7000
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AR-011-916
June 2001

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Executive Summary

Users of respiratory protective equipment are aware that wearing a respirator increases the physical demands imposed on the user. The user is required to breathe through a filter and valve system which offers greater resistance to respiration than breathing naturally. Anecdotal evidence also suggests that wearing a respirator is uncomfortable due to encapsulation and subsequent facial heating. However, there is little quantitative data that indicates the proportion of heat stress related to wearing a respirator as a function of the total Nuclear, Biological and Chemical (NBC) protective ensemble. Therefore, the aim of this pilot study is to use the novel technique of Thermal Imaging (TI) to assess the heat status of the face and the thermal burden associated with wearing the S10 respirator and to determine if design modifications are required to reduce the thermal load.

In this study we recorded the physiological and psychophysical responses, together with the thermal images of the faces in four healthy males. Each subject completed two 45 min trials consisting of acclimation, treadmill walking and a resting phase under a hot ambient environment, while wearing the UK MK IV protective overgarment with (MASK) and without (CON) the S10 respirator.

Generally, there was no additional heat stress recorded while wearing the S10 respirator. As expected subjects reported their face as being more unconfortable while wearing the S10 respirator than without. It is therefore recommended that the design of the S10 respirator require alteration to address user comfort and acceptance, however no modifications are required to reduce thermal load.

Contents

1. Introduction

It is well accepted that wearing a respirator[1] increases the physiological load imposed on the user. However, there is little quantitative evidence of the impact of respiratory protection on thermal strain imposed on the user as a function of the total individual protective ensemble (IPE). A study by Caretti (2000) found that there was no significant change in the thermal load imposed by wearing the US M40A1 respirator with cotton overalls above that experienced while just wearing the overalls. The physiological load associated with wearing a respirator can be attributed to a number of factors. Primarily, increased respiratory resistance (on inhalation and exhalation) and the encapsulation of the face and its influence on heat exchange. There are also the psychological effects of wearing a respirator such as comfort and user acceptability.

The Australian Defence Force in-service Nuclear Biological and Chemical (NBC) defensive respirator is the UK S10 (S10). This is the not the only NBC respirator the ADF holds however it is the most common and is therefore the focus of this study. The S10 is a full face-piece[2], close fitting[3], negative pressure[4] respirator. It is a butyl rubber respirator with coated polycarbonate eyepieces, weighing less than 800 grams. The respirator is fitted with an inner mask to reduce dead space[5] and a drinking tube to facilitate hydration in a contaminated environment. The S10 is manufactured in four sizes (size 1 - largest to size 4 - smallest).

Of particular importance to the thermal load imposed by the S10 are the materials from which the mask is constructed and the airflow through the mask. The materials that constitute the S10 respirator are primarily poor conductors of heat and therefore act to insulate against the removal of heat from the face. However, the design of the mask allows airflow across regions of the face to ameliorate facial cooling. The pattern of airflow through the mask can be explained through a cycle of respiration. During inhalation, air is drawn through the filter, over the face and eyepieces from both the left and right sides. This process also acts as a demister/anti-fogging mechanism for the eyepieces. The air then passes into the inner mask through a hole between the eyepieces at the bridge of the nose, and finally into the lungs. On exhalation the expired air passes into the inner mask and is expelled through the outlet valve at the front of the mask. This pattern of airflow through the mask allows for regional evaporative cooling of the face. Therefore it is expected to observe a distinct thermal image of the face upon removal of the S10. That is, some areas of the face may be relatively cool due to evaporative cooling, while others may be warm to hot as a consequence of being insulated.

[1] The term respirator and mask can be used interchangeably.
[2] Full face-piece refers to the whole face being encapsulated by the respirator.
[3] Close fitting refers to the fact that the mask relies on forming an intimate seal with the face.
[4] Negative pressure refers to the mode by which filtered air is drawn into the respirator. For example, on inhalation a negative pressure is created inside the respirator drawing air through the filter into the lungs.
[5] Dead space is the volume of air that is not exchanged through a cycle of respiration.

This pilot study aims to use the novel technique of Thermal Imaging (TI) to assess the heat status of the face whilst wearing a respirator. The present study also intends to determine the thermal strain (if any) associated with the S10 respirator on an individual while wearing IPE. The results are aimed primarily at modifying respirator design to minimise any such thermal burden.

2. Methodology:

2.1 Subjects:

Four healthy, medically fit, males (age 31 ± 4.5 yr, height 173.3 ± 6.5 cm, weight 81.5 ± 9.3 kg; mean ±SD) volunteered as subjects following an initial briefing on the purpose and demands of the trial. Subjects were familiar with the use of the S10 respirator. They gave written informed consent, and the procedures were approved by the Australian Defence Medical Ethics Committee (ADMEC Protocol 203/99).

2.2 Experimental:

The physiological, psychophysical and thermal effects of the S10 respirator were assessed during a typical operational scenario under controlled laboratory conditions. There were two experimental conditions consisting of one while wearing the S10 (MASK) and the other without (CON). Each subject completed the two trials in balanced order at the same time of the day, at least one-day apart and while wearing standard military uniform (DPCU)[6] and a UK MK IV protective overgarment[7] with their own foot wear. Butyl rubber gloves were not worn so as to facilitate the donning and doffing of the S10 respirator (Avon, UK). During the control trial, the hood of the UK MK IV protective overgarment was worn and the zip fastened to the point where the subject's chin made contact with their chest. Each subject was fitted with their own S10 respirator that had previously been assessed for fit using a quantitative PortaCount Plus fit test (PortaCount Plus 8020, TSI, St. Paul MN, USA) protocol TB 29CFR1910.139. All subjects achieved a mean fit factor of greater than 7000, which represents a good respirator fit.

Subjects were fitted with a polar heart rate (HR) monitor (Polar Accurex, Electro Oy, Finland) and rectal thermistor (T_{re}: YSI 409, Yellow Springs Instruments, OH, USA) which were logged at 1-minute intervals. Tympanic temperature (T_{ty}) was measured in triplicate by an infra red thermometer (First Temp, Genius, Sherwood IMS 6339, USA) at the end of each phase within a trial. Thermal sensation (TS) and thermal discomfort (TD) of both the face and body were recorded using a 13-point and 5-point scale respectively (adapted from Gagge, *et al.* 1967). Relative Perceived Exertion (RPE) was recorded for the whole-body using the 13-point Borg scale (Borg, 1985). A Thermal

[6] Australian Disruptive Patterned Combat Uniform
[7] United Kingdom Mark IV chemical biological protective overgarment.

Image (TI ±0.2°C) of their face was recorded at a distance of 2m using an Inframetrics 760 camera (Inframetrics 760, Inframetrics Inc, Billerica MA, USA) connected to a video cassette recorder (Panasonic, Model NV SD20, Japan). Images were recorded in black and white for later analysis. The TI of each subject's face was recorded with the UK MK IV hood pulled down, firstly in anterior plane, followed by the left, right, and finally the posterior view, each for a total of 5 seconds.

After preparation and instrumentation, subjects entered the environmental chamber set at 30°C and 60% relative humidity. There were four phases within each 65 minute experimental session; seated baseline (20 min), mask acclimation (10 min), moderate exercise (30 min of walking) and seated rest (5 min). All parameters (HR, T_{re}, T_{ty}, TS, TD and TI) were recorded at the end of each phase. The TI was recorded as the subject doffed the S10 respirator and pulled the hood down.

An outline of the protocol is as follows: Subjects rested for 20 minutes (seated baseline) without wearing the S10 respirator to obtain stable baseline measures. In the masked condition subjects then donned the S10 respirator and were allowed to acclimatise for a further 10 minutes (mask acclimation). Following preparation and initial rest periods subjects exercised on a treadmill (Austradex, Preston, Australia) for 30 minutes, at 5 km/h and 0% gradient with or without the mask depending on their allocated condition (moderate exercise). Prior to the completion of the 30 minutes exercise, RPE was recorded for the whole-body work effort. Finally, in both conditions subjects were then allowed to rest for 5 minutes without the S10 respirator but with the hood worn as previously described (seated rest).

2.3 TI analysis:

ThermaGram® Version 5.0 software (ThermaGram® Version 5.0, Inframetrics Inc, Billerica MA, USA) was used for the TI analysis. Windows of 12 x 24 pixel's (width x height, approximately 2cm^2) were generated from which mean skin temperatures were recorded from 16 different regions of the subject's face. Eleven of the regions selected are presented in Figure 1 below, with sites measured on the left (not shown) and right sides of the face.

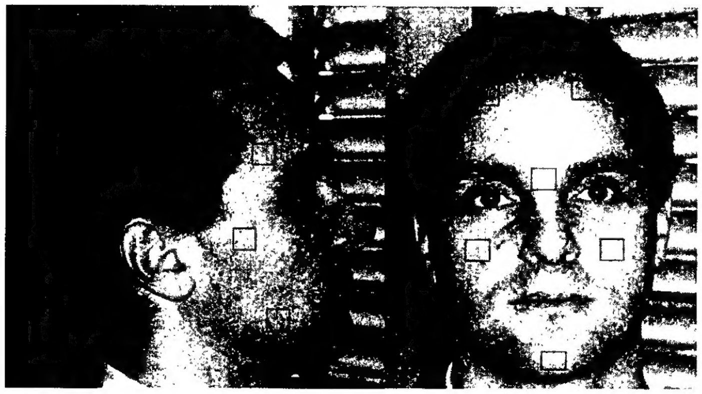


Figure 1. *Subject's face (right and anterior view) with TI measurement sites indicated (boxed). Note: The location of measurement sites for the left view are identical to those shown for the right side of the face*

Digital pictures were used to determine where measurements should be taken for each individual due to varying face shapes and mask positions. The abbreviations used for the 16 regions of the face are presented in Table 1 below.

Table 1. *TI Measurement locations and their abbreviations used in the analyses from the Front, Left and Right Sides of the face.*

Front	Left	Right
ARE - Above Right Eye *	LT - Left Temple *	RT - Right Temple *
ALE - Above Left Eye *	LFE - Left Front Ear *	RFE - Right Front Ear *
RFC - Right Front Cheek	LN - Left Nose	RN - Right Nose
LFC - Left Front Cheek	LM - Left Mandible *	RM - Right Mandible *
CN - Chin *	LCN - Left Chin *	RCN - Right Chin *
NB - Nose Bridge		

** In direct contact with butyl rubber of mask*

2.4 Statistical Analysis:

A 2-way repeated measures ANOVA (2 (treatment) x 4(time)) was used to analyse the dependent variables (T_{re}, T_{ty}, HR, TI & Psychophysical; TS, TD, RPE). Similarly, due to the large variation in the between subject baseline core temperatures, a 2-way repeated measures ANOVA (2(treatment) x 3(time)) was also used to analyse the TI data as differences taken from the end of each experimental phase (ie. end of mask acclimation, moderate exercise and/or final seated resting period) and baseline measurements (initial seated baseline). Significant differences were isolated at $p<0.05$. Data are reported as means ±SD unless otherwise stated. Non-parametric statistics were also employed with similar findings to the standard parametric test described above.

3. Results/Discussion:

3.1 Physiological/Psychological measures:

The measurement of core temperature is crucial to the determination of physiological strain during heat-stress. A standard measure of deep body core temperature is rectal temperature (T_{re}). It represents heat storage within the body and may indicate possible impending heat-illness. Hence, as observed in Figure 2(a), mean core temperature ($\check{T}_{re}$) was unaffected by the use of the mask during this operational scenario, shown clearly by the similarity of the two plots ($p>0.05$), similar to the finding of Caretti (2000). However, there was an expected significant increase in $\check{T}_{re}$ over the duration of the trial ($p<0.05$) irrespective of experimental condition. As shown in Figure 2(b), there is a large variation in baseline T_{re} between subjects, with two starting relatively high and two low. This elevation in baseline T_{re} was probably due to differing acclimatisation status, fitness levels and/or higher prior physical activity levels of the former two participants from those of the latter. Despite these finding, T_{ty} was observed to be significantly higher when masked (M=38.2±0.33°C) than when unmasked (M=38.0±0.42°C) after 30 min of walking exercise ($p<0.05$). This was probably concomitant with the influence from the mask retaining heat, causing contamination of this type of measurement.

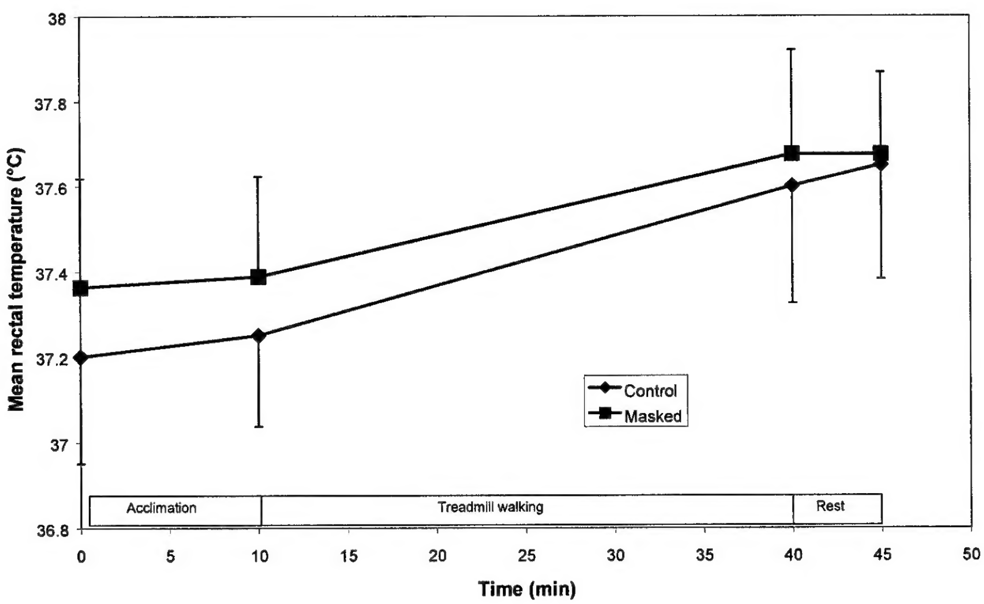


Figure 2 *(**a**). Mean rectal temperature ($\check{T}_{re}$) during mask (MASK) and control (CON) experimental conditions.*

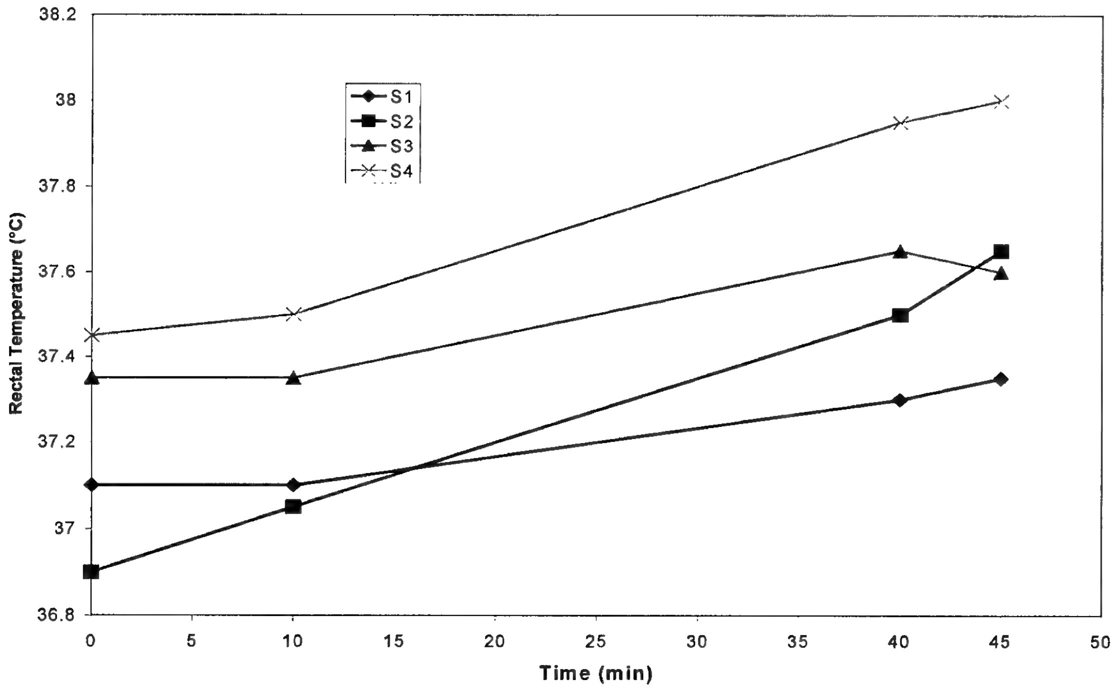


Figure 2 ***(b).*** *Individual subject profiles on rectal temperature (T_{re}) during unmasked (CON) conditions. Note the divergence between subjects 1 & 2 to subjects 3 & 4, particularly at baseline.*

Similarly, mean cardiovascular strain, as measured by heart rate, was concomitant with the core temperature response. That is, mean heart rates were similar across conditions ($p>0.05$), with the masked condition recording slightly lower, but not significant, cardiovascular strain at all time points (Figure 3).

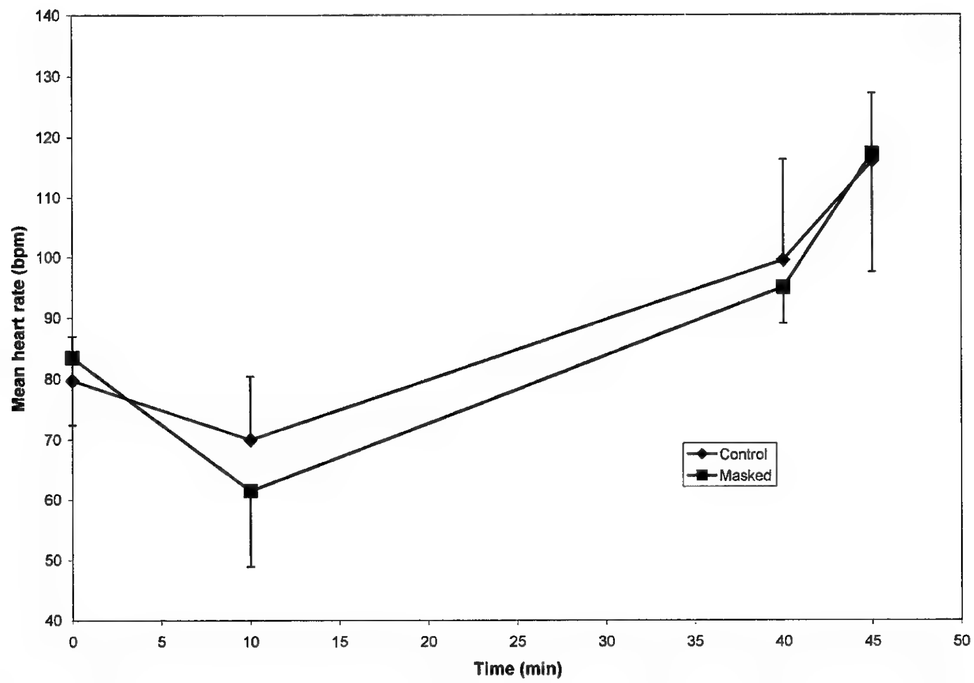


Figure 3*. Mean heart rate for control (CON) and masked (MASK) conditions across the trial.*

The ratings for body temperature, thermal sensation (TS) and thermal discomfort (TD), appeared to be governed by facial temperature. Thermal sensation (TS) ratings of both the face and body for the masked condition tended to be hotter than the unmasked, although not significant (All, $p>0.05$). Similarly masked subjects tended to report greater levels of thermal discomfort of both the face and body than when unmasked (All except post moderate exercise for the face, $p>0.05$) indicative of stronger influences of facial encapsulation. These subjects reported thermal discomfort of the face as being significantly ($p<0.05$) more uncomfortable after 30 min of exercise compared to being unmasked (Figure 4). Perception of work effort (RPE) was similar for both conditions ($p>0.05$), with the masked condition recording marginally higher levels of perceived exertion. This is possibly a result of the increased work required to breathe through the respirator and/or the influence of possible higher facial temperatures and the lack of sweat evaporation from regions of the face.

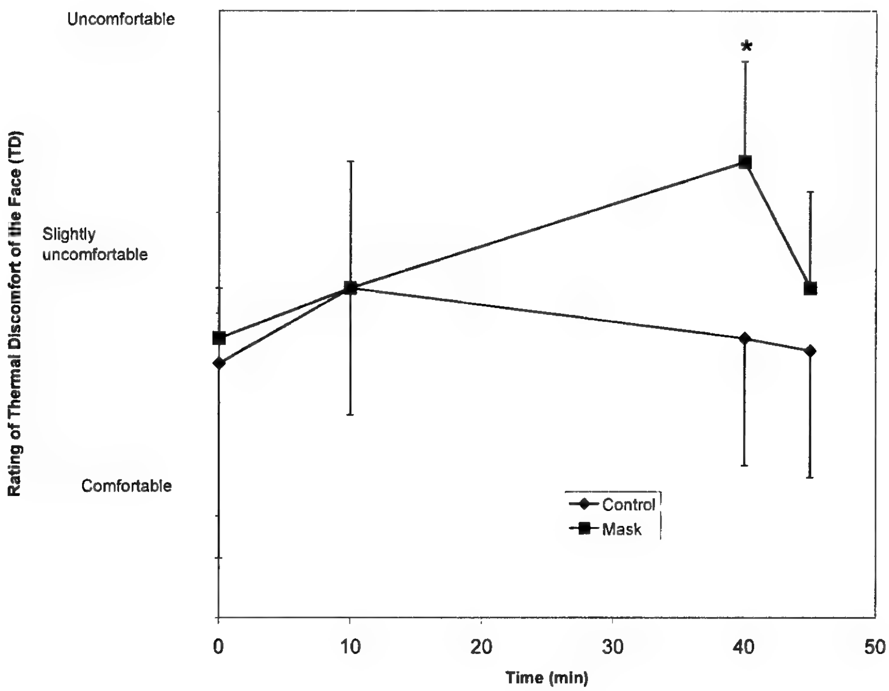
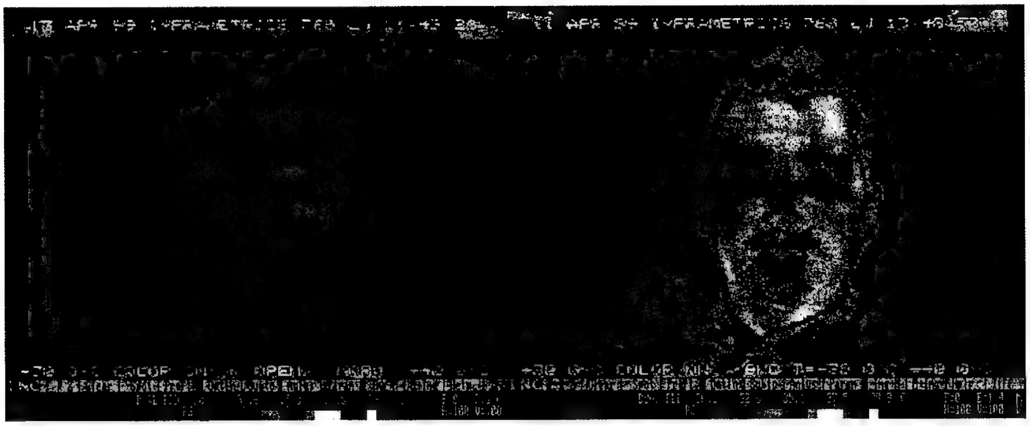


*Figure 4. Mean thermal discomfort ratings of the face during control (CON) and masked (MASK) trials. * p<0.05*

3.2 TI measures:

No significant differences (p>0.05) in skin temperature were observed between the masked and control conditions over time for any of the sixteen TI regions measured. For each of the sixteen TI regions, baseline skin temperatures were subtracted from those recorded at the end of each phase across the trial, to reduce the influence of large inter-subject baseline variations. No significant differences (p>0.05) in mean skin temperature change scores measured by TI (ie. baseline-timepoint) were observed.

Although no statistically significant results were recorded for the TI analysis, two major trends were observed. Firstly, areas in direct contact with the butyl rubber (See Table 1. Indicated by *) of the S10 gas mask tended to be hotter than those in the uncovered control condition (refer to Annex B). Conversely, areas encapsulated by the mask that were ventilated tended to be cooler than those in the uncovered control condition (refer to Annex B). An example of these results is shown in Figure 5, refer to Annex C for the complete set of TI images.



Control Mask

Figure 5. Thermal Image (TI) of one subject during control (CON) and masked (MASK) conditions after 30 minutes of exercise. Note the temperature differences between the control and masked conditions.

3.3 Limitations:

The major limitations of this experiment are possibly due to large inter-subject differences, uncontrolled prior physical activity performed by each subject, the small sample size used and the delay in TI data collection for the left and right sides of the face. Furthermore different facial sweating patterns of each subject, the fitness of each subject, and therefore variation in the onset of sweating between subjects may have contributed to inconclusive results despite accounting for individual baseline variations in all parameters.

4. Conclusions:

Acknowledging the limitations noted above, this pilot study clearly demonstrated that wearing a S10 respirator under moderate levels of exercising heat-stress imposed no additional thermal load above that experienced during maskless activities. Nevertheless, the mask partially inhibited evaporative cooling of the face giving the user the perception of being more heat stressed than when unmasked, which was not matched by the recorded physiological strain. A rise of approximately 0.5°C in the TI temperature of the skin was apparent for those regions directly under and in contact with the butyl rubber of the mask. However, regions encapsulated by the mask but ventilated by the inspired air provided adequate means for evaporative cooling of the face.

5. Recommendations:

It is recommended that the design of the respirator require no significant alteration to reduce any perceived thermal load. Nevertheless, by minimising the amount of butyl rubber in direct contact with the surface of the face, small gains on user acceptability and comfort could be achieved. It may prove to be more important to design a mask with greater user comfort, as this may be more influential on user acceptability than any thermal load imposed by the respirator. However, the potential gains are limited as the amount of butyl rubber in direct contact with the face determines the quality of the face seal and therefore the level of respiratory protection offered.

6. References:

Borg, G., 1985. An Introduction to Borg's RPE-Scale, Ithaca (NY): Movement Publications, p1-26.

Caretti, D.M., 2000, Quantifying the Heat Stress Attributable to Respirator Wear, *Proceedings of International Society for Respiratory Protection*, Sydney, Australia.

Gagge, A.P., Stolwijk, A.J., & Hardy, J.D. 1967. Comfort and thermal sensations and associated physiological responses at various ambient temperatures, *Environmental Research* 1:1-20.

Appendix A: Descriptive Statistics of the Physiological and Psychophysical Data for each Experimental Phase and Condition

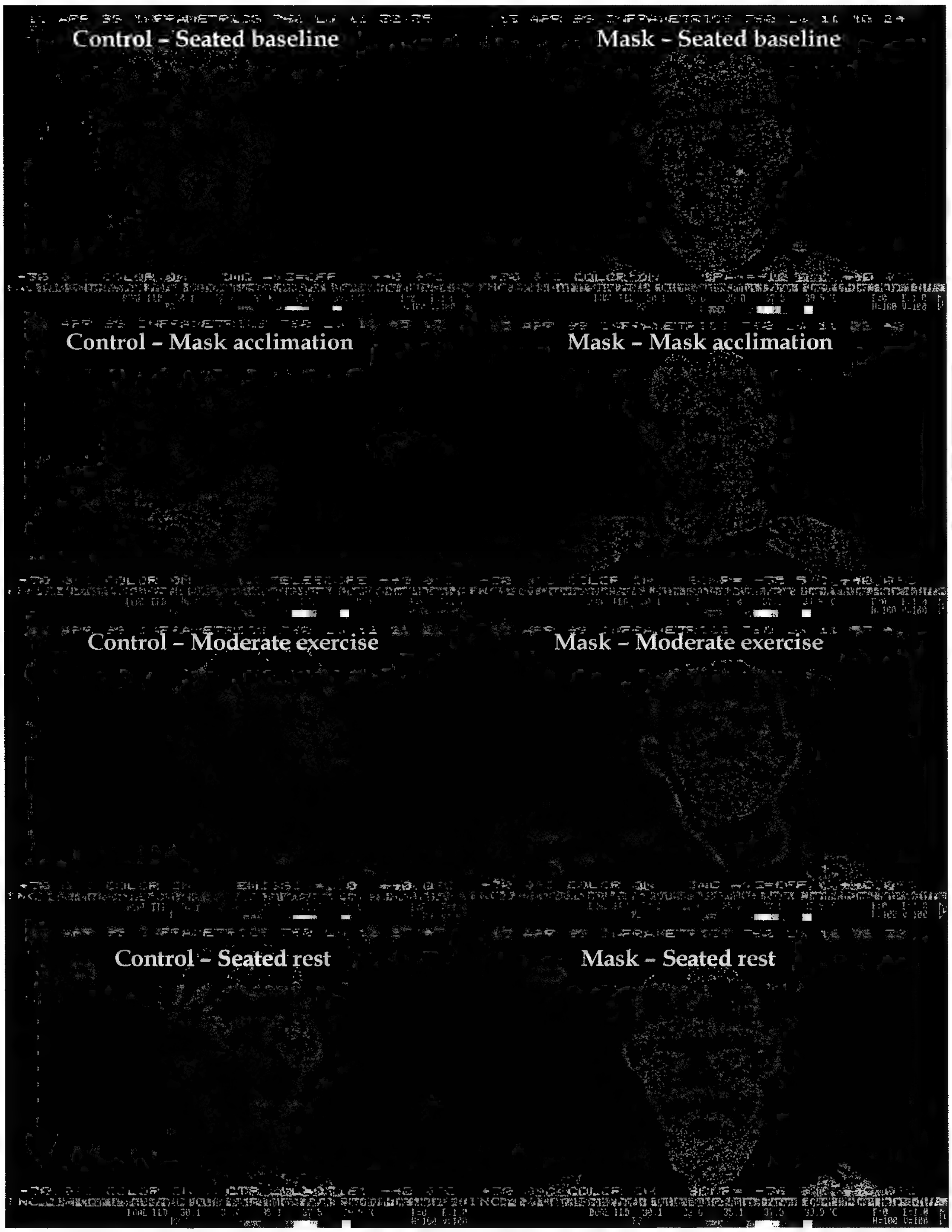
	Seated Baseline		Mask acclimation		Moderate Exercise		Seated Rest	
Measure	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Tre_CON	37.2	0.2	37.3	0.2	37.6	0.3	37.7	0.3
Tre_MASK	37.4	0.3	37.4	0.2	37.7	0.2	37.7	0.2
TSface_CON	8.5	1.0	8.8	1.5	8.3	1.6	7.6	0.6
TSface_MASK	8.6	0.5	9.1	0.3	9.4	0.3	8.4	1.0
TSbody_CON	9.3	0.9	9.1	0.9	9.6	1.1	9.0	0.7
TSbody_MASK	9.4	0.5	9.4	0.5	9.7	0.2	9.4	0.5
TDface_CON	1.8	1.0	2.1	0.6	1.9	0.6	1.8	0.6
TDface_MASK	1.9	0.3	2.1	0.6	2.8	0.5	2.1	0.5
TDbody_CON	2.1	0.6	2.1	0.6	2.8	0.5	2.5	0.4
TDbody_MASK	2.3	0.5	2.3	0.5	2.9	0.5	2.5	0.4
HR_CON	82.3	23.5	83.5	16.0	105.8	23.1	93.8	20.8
HR_MASK	81.5	20.7	82.8	23.1	105.0	26.3	88.0	27.3
Tty_CON	37.8	0.3	37.6	0.5	38.0	0.4	38.0	0.4
Tty_MASK	37.9	0.2	38.0	0.4	38.2	0.3	38.2	0.3
RPE_Con					9.6	2.8		
RPE_Mask					10.0	2.4		

Appendix B: Descriptive statistics of the Thermal Image Data for each Experimental Phase and Condition

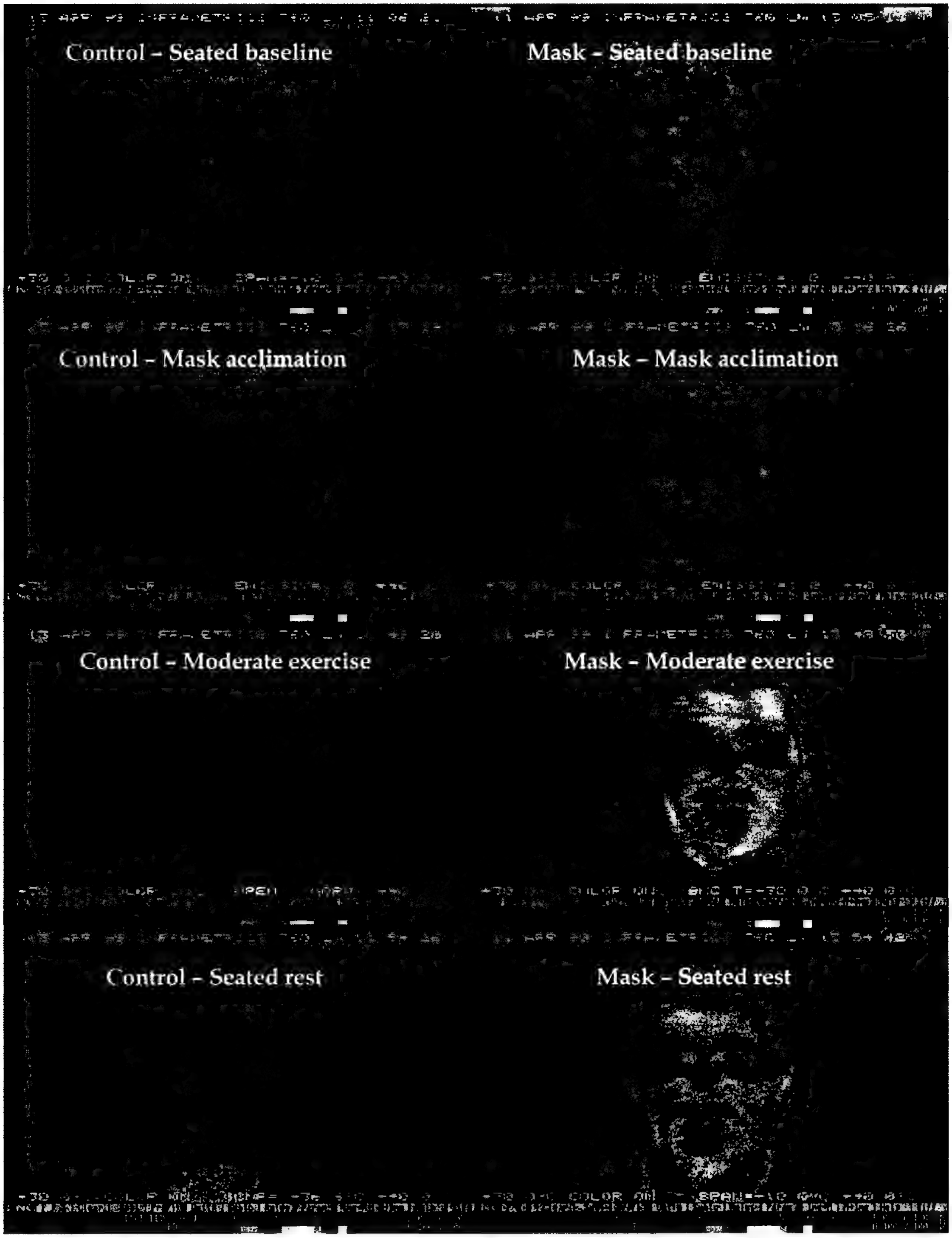
	Seated Baseline		Mask acclimation		Moderate Exercise		Seated Rest	
TI Region	Mean	SD	Mean	SD	Mean	SD	Mean	SD
ARE_CON	34.6	0.3	34.8	0.5	34.8	0.8	34.4	1.2
ARE_MASK	34.4	1.0	34.7	0.8	35.8	0.4	35.2	0.8
ALE_CON	34.7	0.6	34.8	0.5	35.1	0.5	34.4	1.2
ALE_MASK	34.7	0.8	34.9	0.6	35.9	0.5	35.3	0.5
RFC_CON	34.6	0.7	34.9	0.6	34.1	1.0	34.5	0.9
RFC_MASK	34.9	1.1	34.8	1.0	34.5	0.9	34.6	0.8
LFC_CON	34.7	0.7	34.9	0.7	33.9	1.0	34.6	0.8
LFC_MASK	34.9	1.1	34.9	1.1	34.8	1.0	34.6	1.0
CN_CON	34.7	0.4	34.7	0.4	34.9	0.8	35.0	0.5
CN_MASK	34.9	1.2	34.7	1.1	35.0	1.0	34.4	1.4
NB_CON	34.6	0.6	34.9	0.5	34.1	0.7	34.6	0.8
NB_MASK	34.9	1.0	34.9	1.0	34.6	1.3	34.9	0.8
LT_CON	35.0	0.8	35.1	0.7	34.9	0.7	34.6	0.8
LT_MASK	35.2	1.1	35.2	0.6	35.8	0.5	35.4	0.7
LFE_CON	34.9	1.3	35.1	1.1	34.8	1.2	34.4	1.4
LFE_MASK	35.1	1.5	35.3	1.0	35.4	0.9	35.3	0.8
LN_CON	34.8	0.3	34.9	0.2	34.8	0.5	35.1	0.4
LN_MASK	35.2	0.8	35.2	0.8	35.0	0.9	35.0	0.7
LM_CON	35.2	0.7	35.3	0.8	35.1	0.8	35.1	0.8
LM_MASK	35.6	1.0	35.5	0.9	35.6	0.5	35.6	0.6
LCN_CON	34.9	0.5	34.9	0.4	34.7	0.8	35.0	0.6
LCN_MASK	35.0	1.2	35.0	1.0	34.8	1.0	34.7	0.9
RT_CON	34.8	0.6	35.0	0.6	34.8	0.6	34.3	0.6
RT_MASK	35.0	1.1	34.9	0.6	35.5	0.5	35.1	0.7
RFE_CON	34.8	1.1	35.1	1.0	34.8	0.8	34.7	1.0
RFE_MASK	35.0	1.5	35.0	1.0	35.1	0.8	35.2	1.0
RN_CON	34.8	0.2	34.9	0.3	34.8	0.5	35.1	0.3
RN_MASK	35.1	0.9	35.1	0.9	35.0	0.8	35.2	0.7
RM_CON	35.2	0.7	35.2	0.9	35.0	0.6	35.4	0.5
RM_MASK	35.5	0.9	35.5	1.0	35.3	0.5	35.5	0.7
RCN_CON	34.9	0.4	35.0	0.4	34.7	0.7	35.0	0.5
RCN_MASK	35.1	1.0	34.8	1.0	34.4	1.1	34.9	0.9

Appendix C: Anterior Plan Thermal Images of Subjects after each Experimental Phase for both Conditions

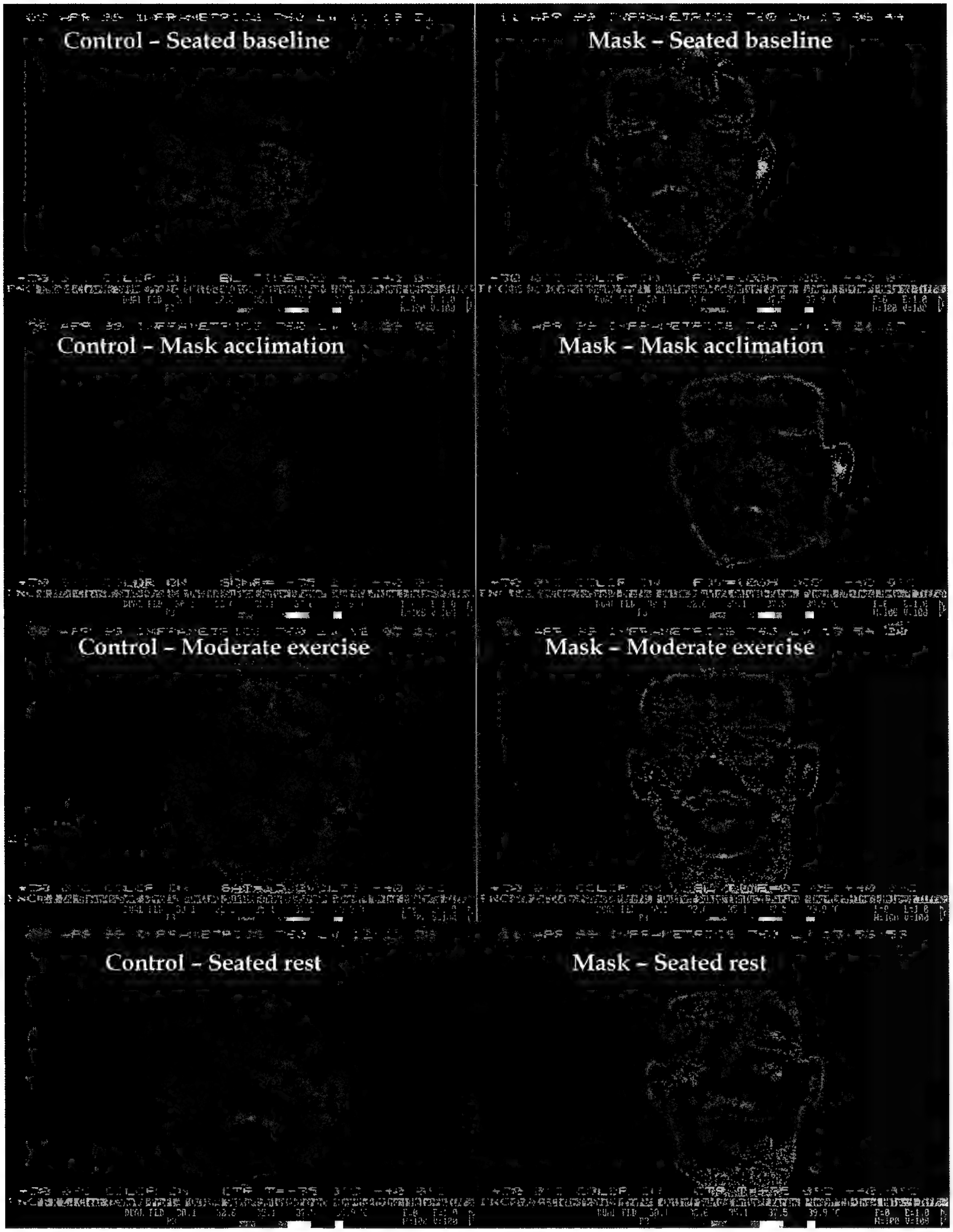
Thermal Image for Subject 1



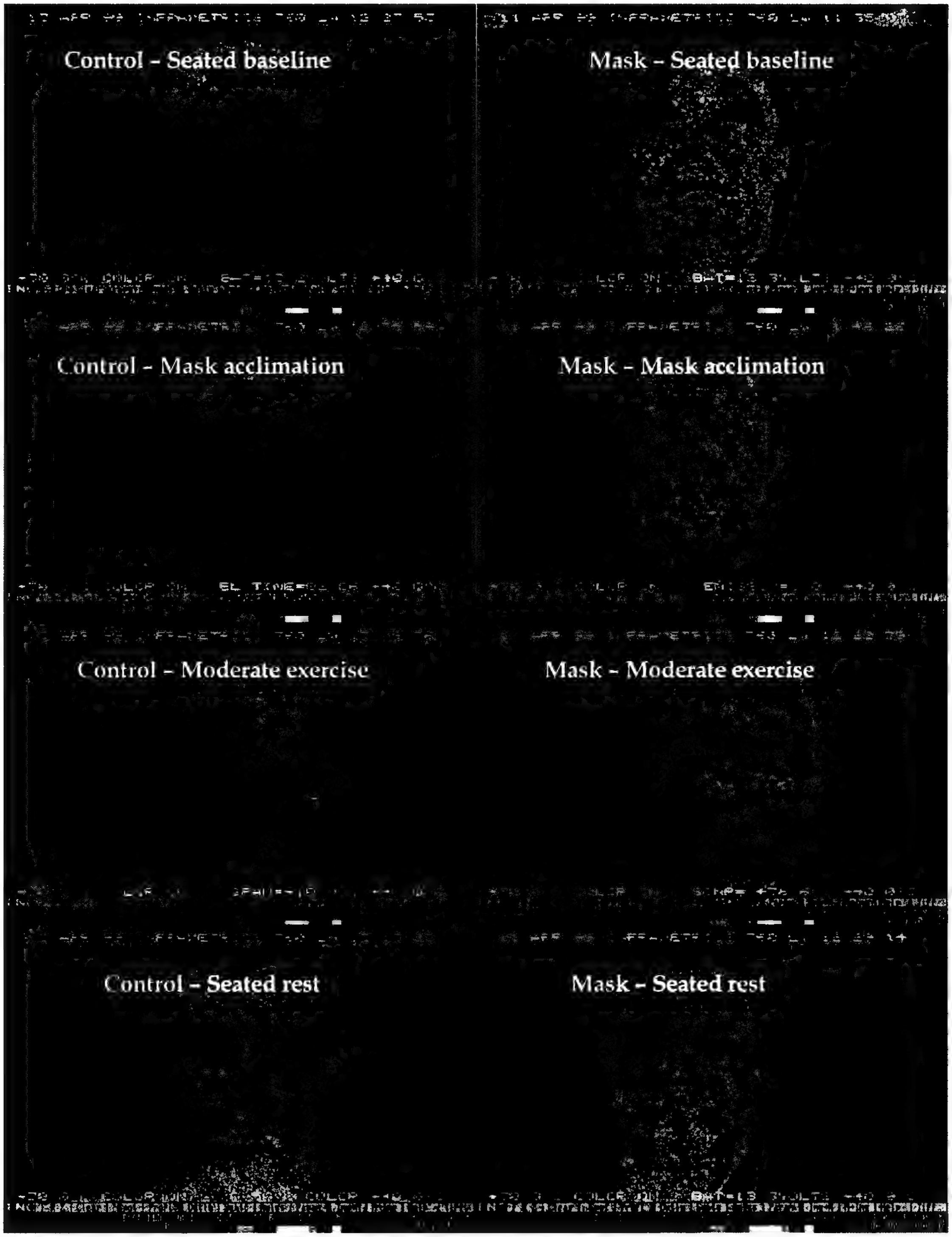
Thermal Image for Subject 2



Thermal Image for Subject 3



Thermal Image for Subject 4



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DOCUMENT CONTROL DATA

1. PRIVACY MARKING/CAVEAT (OF DOCUMENT)

2. TITLE Physiological Burden of the S10 Respirator	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)
4. AUTHOR(S) S. Scanlan and W. Roberts	5. CORPORATE AUTHOR Aeronautical and Maritime Research Laboratory 506 Lorimer St Fishermans Bend Victoria 3207 Australia

6a. DSTO NUMBER	6b. AR NUMBER	6c. TYPE OF REPORT	7. DOCUMENT DATE
DSTO-TN-0380	AR-011-916	Technical Note	June 2001

8. FILE NUMBER	9. TASK NUMBER	10. TASK SPONSOR	11. NO. OF PAGES	12. NO. OF REFERENCES
510/207/1199	M30027	DGLD	20	3

13. URL on the World Wide	14. RELEASE AUTHORITY
http://www.dsto.defence.gov.au/corporate/reports/DSTO-TN-0380.pdf	Director Aeronautical and Maritime Research Laboratory

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

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16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CASUAL ANNOUNCEMENT Yes

18. DEFTEST DESCRIPTORS

NBC protective clothing; Respirators; Thermal insulation; Heat stress (physiology)

19. ABSTRACT

It is well accepted that wearing a respirator increases the physiological load imposed on the user. However, there is little quantitative evidence of the impact of respiratory protection on thermal strain imposed on the user as a function of the total individual protective ensemble (IPE). This pilot study aims to use the novel technique of Thermal Imaging (TI) to assess the heat status of the face and thermal strain associated with wearing the S10 respirator. The physiological (rectal and tympanic temperatures, heart rate), psychophysical (thermal sensation and discomfort, perceived exertion) and thermal effects (thermal imaging) of the S10 respirator were measured in four healthy males (31±4.5yrs). Each subject completed two 45 min trials consisting of acclimation (10 min), treadmill walking (30 min) and rest (5 min) in a hot environment (30°C dry bulb and 60% relative humidity), while wearing the UK MK IV overgarment with the S10 respirator (MASK) and without (CON). Generally, there was no additional thermal strain while wearing the S10 respirator. However, subjects reported thermal discomfort of the face as being significantly ($p<0.05$) more uncomfortable after 30 mins of exercise compared to being unmasked. In conclusion, the mask partially inhibited evaporative cooling of the face giving the user the perception of being more heat stressed than when unmasked, which was not matched by the recorded physiological strain. It is recommended that the design of the respirator require no significant alteration to reduce any perceived thermal load.